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NORTH SEA STORM SURGES

by

R. D. HUNT

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NORTH SEA STORM SURGES

Definition and Generation of a Surge

A storm surge can be defined as a change in sea level due to meteorological causes, a raising of sea level being called a positive surge and a lowering being called a negative surge. They frequently accompany the passage of a depression over or near to a sea area and can last for a period of between one or two hours and a few days. They can occur in any sea region, although most serious surges occur in shallow seas which are either partly or completely enclosed, and their presence is detected by discrepancies between the astronomically predicted tidal heights and those actually observed.

The two meteorological forces most important for the development of surges are firstly the tractive force of the wind on the water surface which is proportional to the square of the wind speed and which results in water being dragged in the general direction of the wind, although being deflected to the right of the wind direction in the Northern Hemisphere by the rotation of the Earth, and, secondly, the effect of changes in atmospheric pressure on the water surface. If the air pressure is reduced then the water surface rises, a fall of pressure of one millibar being accompanied by a rise in the water surface of one centimetre and vice versa. Of these two effects, the wind effect and the static pressure effect, the former is on the whole the more important in shallow seas.

Once having been generated, the surge is propagated according to appropriate laws of motion and if it reaches a coast and is sufficiently large and positive, then flooding may occur in certain circumstances as was the case, for example, on 31 January and 1 February 1953 when flooding was disastrous on the coasts of the Netherlands and eastern England (Grieve (1959)). Alternatively, if the tide is lower than was predicted astronomically, ie in the case of negative surges, then serious navigational problems can arise in shallow water areas with the possibility of large ships running aground. Another point concerning surges in general is that in shallow water the effects of bottom topography become much more noticeable and the surge profile is modified considerably wherever the height of the surge is not negligible compared to the total depth of water, such as near beaches.

To measure the height of a surge, the height of the astronomical tide must be subtracted from the total water height leaving just the effects of the meteorological forces. Thus surges are measured in terms of 'residuals', the residual at a point being the difference between the observed tidal height and the astronomically predicted tidal height at that particular point and time. As an example of the height a surge can attain, residuals of over 12 feet were measured during the 1953 surge in parts of the southern North Sea.

Surges in the North Sea

For most purposes, the North Sea can be considered as a closed, rectangular basin with shallow water at the closed southern end and somewhat deeper water in the north, where the sea opens into the Norwegian Sea. Frequently, a surge is generated to the north-west of Scotland and propagates into the North Sea in the form of a progressive long-wave, being modified by local winds, local coastal features, and, particularly on reaching the shallow southern North Sea, by surge-tide interaction as it does so. The effect of Coriolis force is to cause the wave to travel anti-clockwise round the North Sea, affecting firstly the east coast of Britain as it travels southwards and then onto the Belgian and Dutch coasts. It can sometimes still be identified as it reaches the Norwegian coast. The speed of the surge is about the same as that of the astronomical tide which, being a similar long-wave feature, is propagated in a similar fashion. It takes about 27 hours for the surge to travel from Aberdeen to Bergen on the Norwegian coast.

The effect of wind stress is to pile up the water at the leeward end of the sea, and so northerly or north-westerly winds blowing over the North Sea not only tend to increase the total amount of water in the sea by forcing it to enter at the open northern end, but also to pile up water at the closed southern end. As mentioned above, the water is deflected to the right of the wind direction and so north-westerly winds also have the effect of raising the sea-level on the east coast of Britain.

One point which should be mentioned here is that the southern end of the sea is not completely closed. The narrow Straits of Dover act as a small but important

outlet for excess water during positive surge conditions in the south of the sea.

The most common kind of positive surge is a combination of the two effects described above, part caused by the propagation down the east coast of a surge generated outside the North Sea and part caused by wind effect within the North Sea. On some occasions, however, positive surges develop entirely within the North Sea, either in the extreme northern part, although it is difficult to distinguish these from the first type, or in the southern part with water forced westwards against the south-east coast of England.

The propagation of negative surges is somewhat less easy to explain. A wind over the North Sea from between south-westerly and south-easterly in direction causes a general lowering of sea-level. If the wind field is uniform over the whole sea, then the negative surge appears to occur almost simultaneously at coastal points in the southern North Sea, ie there is little evidence of southward progression. On the other hand, a southerly wind blowing only over the northern part of the sea produces a negative surge there which does appear to propagate southwards down the east coast in a similar fashion to a positive surge.

Surge producing meteorological situations

The meteorological situations which tend to produce surges in the North Sea have been described in some detail by Keers (1966) and, earlier by Corkan (1948). However, a summary of them would be in order here. The most common positive surge producing situation is a depression moving eastwards between Scotland and Iceland, and then either continuing eastwards towards Norway or turning south-eastwards into the North Sea. This situation is characterised by southerly or south-westerly winds over the North Sea which veer to between westerly and northerly behind the south-eastwards passage of a trough down the British east coast. A steady north-westerly wind blowing for many hours or even days over a large part of the sea is a second situation which can give rise to a positive surge. A third situation is a strong wind from between east and north-east blowing over the Thames Estuary and Flemish Bight regions. In this relatively rare case, the surge is restricted to the coast of south-east England and, in particular, the Thames Estuary.

Negative surges are most commonly generated by strong winds between south-westerly

and south-easterly blowing over the sea, and, therefore, often precede the positive surge type caused by the eastwards passage of a depression to the north of Scotland. A negative surge caused by south-westerly winds ahead of a trough is followed by a positive surge after the winds have veered behind it. A depression slow-moving to the west or north-west of the British Isles is another favourable situation for negative surge development with south-westerly winds possibly lasting for several days, and, in this case, the negative surge may not be followed by a positive surge.

The effect of surge-tide interaction is to create a tendency for the positive surge peak, ie the greatest residual, to occur on the rising tide and rarely at high tide, as was shown, for example, by Keers (1968). The surge height generally falls quite rapidly towards the time of astronomically predicted high water. Now for flooding to occur at a particular place there must usually be a large residual of several feet occurring at high water. The main effect of surge-tide interaction is, then, to decrease the likelihood of a particular surge causing flooding in coastal regions where the water is shallow and this effect is important. (The size of the residual required to produce flooding, however, depends on the height of the astronomical tide, and so in cases of very high astronomical tides only a small residual at high water may be sufficient).

An example of a surge occasion is shown in Figs 1 and 2. The first of these charts shows a depression to the north-west of Scotland at 0600 GMT on the 28th September 1969 with strong south-westerly winds ahead of it over the northern part of the North Sea. The second chart, for a time twelve hours later, shows the depression having moved east-north-eastwards to the north-east of Scotland and its associated cold front travelling south-eastwards down the North Sea followed by strong north-westerly winds. Fig 3 is the surge residual diagram for this occasion. The Storm Tide Warning Service (STWS), who are responsible for issuing warnings, plot the residual (in feet) against time at each of the eight reference ports they use, namely Stornoway, Wick, Aberdeen, Tyne Entrance, Immingham (on the Humber estuary), Lowestoft, Harwich (although since 1970 Walton (Essex) has taken over from Harwich) and Southend. The time of astronomically predicted high water is shown at each port by a short vertical line. The passage of a negative surge down the east coast of Britain is clearly shown, this being followed by a positive surge which reaches a peak of 2.2 feet

at Stornoway and 7.4 feet at Southend. A rapid decrease of the surge height can be seen at the shallow water ports in the south just before the time of astronomically predicted high water.

Special cases of the positive surge-producing meteorological situations involving resonance between the tide and the forces causing the surge are the most likely to give large residuals at high water. The most serious situation arises when a depression moves south-eastwards into the North Sea with a trough swinging south-eastwards behind it at approximately the same speed as the tide. If the wind veers from near westerly in front of the trough to between northerly and north-westerly behind it and simultaneously strengthens a few hours before the time of high water at a particular coastal point, then the residual may be large at high water. This was the case in the 1953 surge (although in this case the trough was not well-defined, the wind veered and increased steadily through the important period).

Frequency of North Sea Surges

To give a figure for the frequency of surges, a more precise definition than was given earlier must be used. STWS define a positive surge as occurring when the maximum residual is two feet or more at high water at more than one of the eight reference ports already mentioned. Similarly, a negative surge occurs if the residual reaches minus two feet or less at high water at more than one of the reference ports.

Using this definition, the average number of positive surges per STWS operational season (which runs from September to April - the period when nearly all the surge-producing conditions arise) has been found to be just over 15 since 1953 when regular data collection began. The amount of data in existence for negative surges is much less than for positive surges as it is only in recent years that the increased draughts of some of the ships in the North Sea have led them to become important; however, as an example of their frequency, there were 10 in the 1970-71 season.

Forecasting of North Sea Surges

The advantages in being able to forecast surges at least a few hours in advance are apparent when one considers the action that can be taken by relevant bodies either to lessen the effect of flooding or to alter the course taken by a ship.

The development of forecasting techniques used by the STWS has been with the

aim of producing a preliminary high water residual forecast one tidal period (ie about twelve hours) ahead for each of the eight reference ports mentioned above, and then a final surge height estimate some hours later. This aim has, to a large extent, been achieved in recent years in the Meteorological Office using a system of empirical formulae which give forecast residuals at the eight ports in terms of parameters found to be significant. Empirical techniques were studied some years before this system was developed by, for example, Dines (1929), Corkan (1948) and Rossiter (1959).

Before describing the system in detail, it is desirable to distinguish between the requirements of forecasting systems for positive and negative surges. The largest difference arises because only the residuals at high water are important in positive surge situations, whereas some idea of the surge profile over the whole tidal cycle is ideally necessary for negative surge forecasting. Only small reductions in depth in some areas may be important to ships' navigators at any time. The other main difference is in the areas which need to be covered by the forecasts. Negative surge forecasting is only useful for shallow water ports on the southern North Sea coast, whereas, although some coasts are more susceptible to flooding than others, positive surges need to be forecast at as many coastal points as possible. On the other hand, predictions for off-shore locations would be desirable during negative surges (in the Thames Estuary and Straits of Dover for instance), although the lack of off-shore tidal observations makes such predictions extremely difficult.

In the main the emphasis has been on forecasting positive surges and so the system has been geared towards high water forecasts at the eight ports. A system of 'twelve-hour' and 'four-hour' surge prediction formulae has been developed by Keers, P E Francis and Hunt (reported in papers to the Advisory Committee on Oceanographic and Meteorological Research). These formulae are applied twelve and four hours respectively before high water at each of the ports, the former serving as the preliminary estimate as required and the latter as the final estimate.

Most of the four-hour formulae produced have been for positive surge prediction and were derived from the large sample of positive surges for which data are now available (about 170 for Southend for example, all occurring since 1953). Much use

was made in the construction of the formulae of the fact that most surges propagate southwards down the east coast and are modified by local winds as they progress. To incorporate this local wind effect into the formulae, areas of the North Sea were used over which the wind was found to be important in determining the surge height at one or more of the ports. There are five of these areas, subsequently called 'wind areas', each of 60 nautical miles radius and all in the western part of the sea as shown in Fig 4. Data have been collected for positive surge occasions since 1953 (using the STWS definition of a surge as stated previously), and, more recently, for all negative surges. The data consists of residuals at various times in the tidal cycle at each of the ports, geostrophic winds over each of the wind areas at hourly intervals for nearly a day, and surface pressure at various points on the east coast and also to the north of Scotland on each surge occasion. Surface winds have also been noted at a few coastal stations. Geostrophic winds are used rather than surface winds in the wind areas because of the greater ease in estimating geostrophic wind over the sea regions.

Multi-regression techniques were used to determine the most significant forecasting parameters at each port (about four or five parameters were chosen from an original list of about forty) and to calculate their coefficients in the regression equations. One important point to arise as a result of this procedure was that the barometric effect was only found to be significant at Stornoway for predicting the surge generated to the north-west of Scotland. At all the east coast ports, the 'southward propagation factor' and the wind effect were dominant. The factors included in the formulae to predict high water residuals are generally, then, the high water residual at one or more ports further north to take account of the progression of the surge and which, owing to the southward movement of the tide, has in many cases already been observed at the time of application of the formulae, and some component of the geostrophic wind in one or more of the wind areas some hours before high water to allow for time lag. Tide-surge interaction is represented in a simple fashion in a few of the formulae. These four-hour formulae have produced surge height predictions with root-mean-square-errors (RMSE) of the regression estimates of about 0.4 ft - slightly less for the northern ports, slightly more for the southern ports. An example of such

a formula, which predicts the high water residual at Southend, is:

$$R_S = 0.29 + 73R_L + 0.38R_I - 0.57R_{L-3} + 0.007V^{330}_{a,t-6}$$

where R_S is the high water residual at Southend (in feet) R_L, R_I are the high water residuals at Lowestoft and Immingham (high water at Lowestoft and Immingham occurring three and seven hours respectively before that at Southend), R_{L-3} is the residual three hours before high water at Lowestoft (this factor is a simple way of representing tide-surge interaction) and $V^{330}_{a,t-6}$ is the 330° component of the geostrophic wind (in knots) in wind area 'a' (refer to Fig 4) six hours before high water at Southend. The RMSE of the regression estimates for this formula is 0.46 ft while the maximum error is 1.2 ft.

A second example is the four-hour formula for Lowestoft:

$$R_L = 0.34 + 0.94R_T + 0.014V^{020}_{a,t-2} + 0.020V^{330}_{y,t-5}$$

where R_L, R_T are the high water residuals at Lowestoft and Tyne, $V^{020}_{a,t-2}$ is the 020° component of geostrophic wind in area 'a' two hours before high water at Lowestoft and, finally, $V^{330}_{y,t-5}$ is the 330° component of the geostrophic wind in area 'y' five hours before Lowestoft's high water. This gives a RMSE of the regression estimates of 0.44 ft. The formulae for the other ports are similar to these, some using surface wind values at Fair Isle as a predictor rather than geostrophic wind over a wind area.

A formula has also been calculated to be used in the easterly surge situation in the Thames Estuary with a residual prediction for Southend, but this has been derived from a rather small sample and, consequently, less confidence can be placed in results from its application.

The twelve-hour formulae were derived from balancing sets of positive and negative surges to allow them to be used in a greater variety of situations. They could then indicate whether a positive or negative surge or no surge at all was going to occur during every tidal period. Another required goal was to make the constant term in the formulae equal to zero so that no surge-producing forces would lead to no surge. It will be noticed, for instance, in the four-hour formula for Southend that a surge of 0.29 ft is predicted to occur at Southend if no surge was observed at Lowestoft and Immingham and there is no wind. This arises because the formula was derived from a sample of positive surges and is only applicable, therefore, in a positive surge situation.

Apart from these differences, the twelve-hour formulae were calculated in much the same way as the four-hour ones. In operation, because the forecast is for 12 hours ahead, values for the various wind components and high water residuals need to be forecast some hours ahead for inclusion in the formulae. As a result of this, these formulae are less accurate than the four-hour ones in practice. As an example of a twelve-hour formula, the high water residual at Immingham is predicted using

$$R_I = 0.04 + 1.19R_T + 0.019V^{060}_{y,\ t-1} + 0.010V^{290}_{x\ t-2}$$

The symbols have similar meanings to those in the four-hour formulae.

The Southend and Lowestoft twelve-hour formulae have rather large positive constant terms in spite of the use of a balancing set of positive and negative surges which was hoped to eliminate them. As explained earlier, collection of data for negative surges only began recently and only when more data have been obtained will this rather undesirable feature be eliminated.

A twelve-hour formula of special interest is that for Stornoway. It is:

$$R_{st} = R_{st,\ t-12\frac{1}{2}} - 0.042\,\Delta B_{st}$$

Here, R_{st} is the high water residual at Stornoway, $R_{st,\ t-12\frac{1}{2}}$ is the residual at Stornoway at the previous high water and ΔB_{st} is the forecast change in surface pressure at Stornoway over the tidal period. In fact, the coefficient of the ΔB_{st} term is higher than would be expected from applying the static pressure law, a forecast fall in pressure over the twelve hour period of one millibar leading to a forecast increase in residual at Stornoway of 1.28 cm rather than 1 cm. This is probably due to the existence of continental shelf waves causing an enhanced pressure response of the sea surface on the western side of a land mass if a continental shelf exists, and serves as an example of one of the advantages of this empirical method. It has implicitly taken into account an effect which would have been difficult to include explicitly using this or any other technique.

Other Formulae

At the present time, only a four-hour final estimate of negative surge height for Southend high water has been developed but not yet used operationally. As the amount of data recorded for negative surges is appreciably less than for positive

surges and their propagation appears not to be as straightforward, the formula is not as accurate as the corresponding positive surge formula. Another recent move has been an attempt to construct a twelve-hour low water formula for Southend to attempt, at least in part, to meet the requirement for forecasts of negative surges. Here, the data problem is even worse and much more will be needed before it can be put into practice.

A further recent development in the empirical technique has been to produce formulae which use observed and predicted tidal heights rather than residuals as parameters. This was done after investigations had revealed that there was a marked tendency for the formulae to predict large residuals less well than smaller ones for the southern ports and for the errors to be mainly under-predictions. A possible solution to this problem was to give extra weighting to the important surges in the sample from which the formulae were derived. However, these were not necessarily those with the largest residuals but those with the largest observed heights, ie largest heights of tide plus surge, and so a new set of formulae were calculated using observed and predicted heights. The largest ten or so observed heights were given double weighting, and this corrected to a small extent the underprediction problem. An example of a 'weighted formula' is the four-hour one for Southend

$$O_s = -0.4 + 1.05P_s + 1.02R_L - 0.57R_{L-3} + 0.009V_{a,\,t-6}^{030} + 0.008V_{a,\,t-10}^{220}$$

where O_s is the height of tide plus surge at Southend, P_s is the tidal height predicted astronomically for high water Southend and the other symbols are as before.

A final point regarding the formulae concerns the use of the linear form of the wind term rather than the quadratic form as a parameter the latter might having been expected from the expression relating the surface stress to the square of the wind speed. Early formulae were calculated using V^2 but results have shown that they are not improved by doing this and so, because of the obvious operational advantage, the linear form is used.

Other Developments in the Surge Forecasting Field

The empirical methods described in the previous section have been largely successful, producing, on the whole, quite accurate predictions on the occasions

when they have been applied. In fact the errors the formulae give are often of the same order as errors in the astronomical predictions. Also, they are cheap both in production and application. Another advantage, the ability to include factors implicitly, has already been discussed.

Navigational considerations have, however, led to the idea that at some time in the future a routine service should be introduced, issuing forecast heights of tide plus surge on a daily basis. This would, ideally, involve forecasting for low water and possibly other points in the tidal cycle as well as for high water and extensions of the empirical technique to meet this requirement would produce problems. The method is inherently inflexible. The formulae can only be applied at fixed places and times and use as predictors winds and residuals at fixed places and times. Not only are the effects of possibly important small-scale features and of rapidly changing meteorological conditions omitted, but also any extension to forecasting for new places and for different times involves the acquisition of vast amounts of data which may take an appreciable time to amass. The result of such a development would be a rather cumbersome set of formulae and the basic simplicity of the technique could be lost. A limited extension to include, for instance, low water forecasts at some southern North Sea ports would, nevertheless, be reasonable and it was with this aim in view that the low water formula for Southend, already described, was developed.

Other developments in surge forecasting methods have taken place in this country at the Institute of Coastal Oceanography and Tides (ICOT) and at the National Institute of Oceanography (NIO). At ICOT, a numerical model for the water surrounding the British Isles is being developed (Heaps (1969)). The hydrodynamical equations describing the motion of the sea produced by meteorological forces are linearised, integrated with respect to depth and solved using a finite difference scheme and a fine grid. Recently, a non-linear model for the shallow waters of the southern North Sea and Thames Estuary has been added to this basis and attempts to reproduce the non-linear surge-tide interaction effects actually observed have been made.

A major problem with these models is the introduction of meteorological data. If they are to run operationally, some form of wind or wind stress field and surface pressure field will be required as input. Test runs of the models have been made using as input estimated surface wind values over certain sea areas and, more recently, the surface pressure field to calculate both the barometric effect and the geostrophic wind effect. In the future, some kind of output from the numerical weather model will clearly be required although the exact form is uncertain.

At NIO, an analogue model has been constructed, sets of response functions having been calculated for a large number of points in the North Sea giving the response of the sea surface to a variety of surge producing forces acting over small areas. Providing the surge is treated as linear, then the total response at each point to forces acting over the whole sea can be found by adding all the contributions from the small areas.

Finally, it is important to note that all methods for surge forecasting suffer from lack of off-shore tidal data, making it impossible to determine surge heights at any points other than on coasts. Off-shore tidal measurements would seem to have a vital role to play in the future of surge forecasting.

R D HUNT

References

Corkan, R. H, — Storm Surges in the North Sea. US hydrogr. Off., Misc 15072, Vols. 1 and 2, 1948

Dines. J. S, — Meteorological Conditions associated with High Tides in the Thames. Geophys. Mem., Lond., No 47, 27-39, 1929

Grieve, Hilda, — The Great Tide. Chelmsford, Essex County Council, 1959

Heaps, N. S, — A 2-dimensional Sea Model. London Phil. Trans. R. Soc., A, 265, 93-137, 1969

Keers, J. F, — The Meteorological Conditions leading to Storm Surges in the North Sea. Met. Mag., London, 95, pp. 261, 1966

Keers, J. F, — An Empirical Investigation of interaction between Storm Surge and Astronomical Tide on the East Coast of Great Britain. Hamburg, Dt. hydrogr. Z., 21, 118-125, 1968

Rossiter, J. R, — Research on Methods of Forecasting Storm Surges. Q J Royal Met. Soc., 85, 262-277, 1959

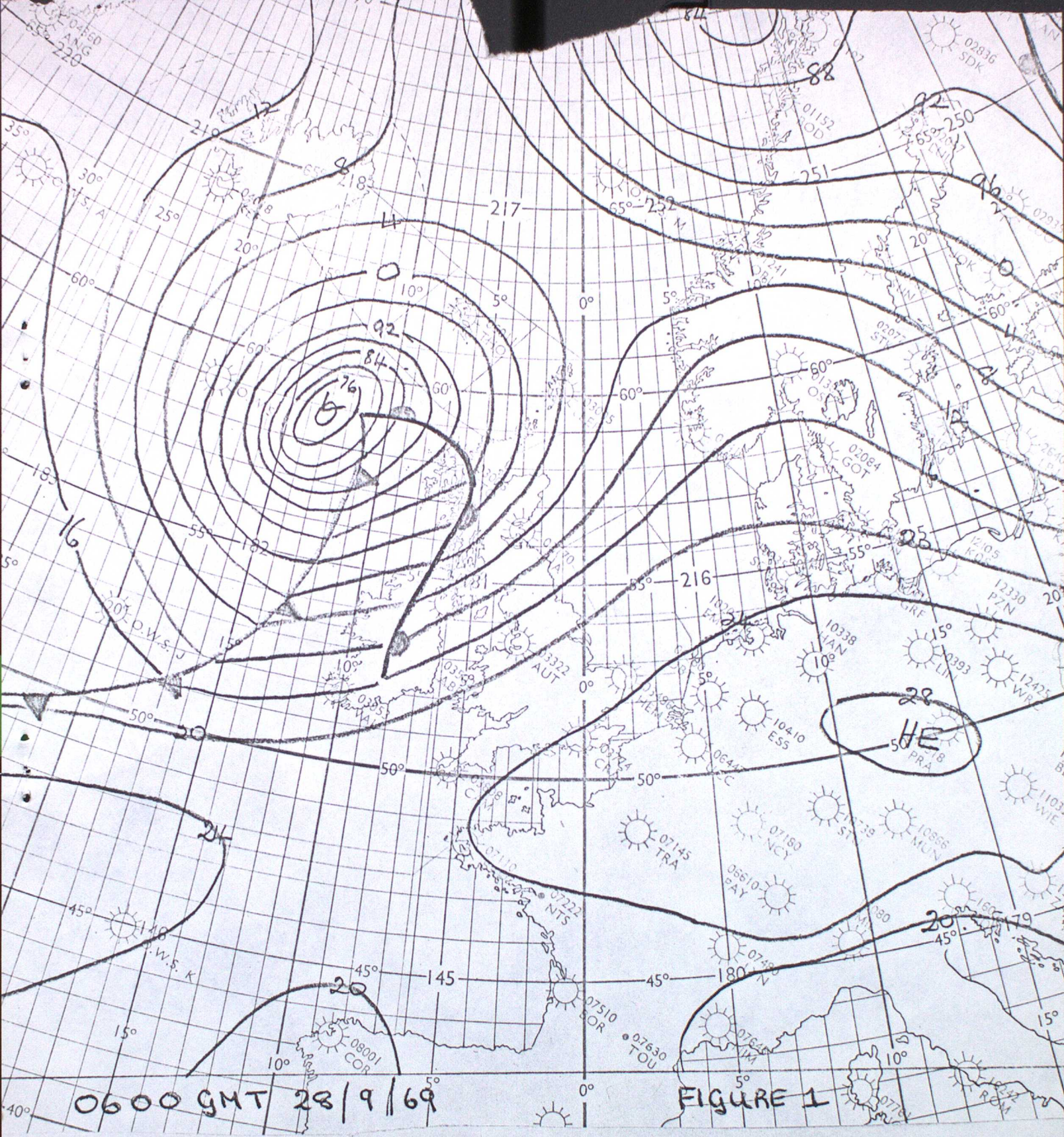

FIGURE 1

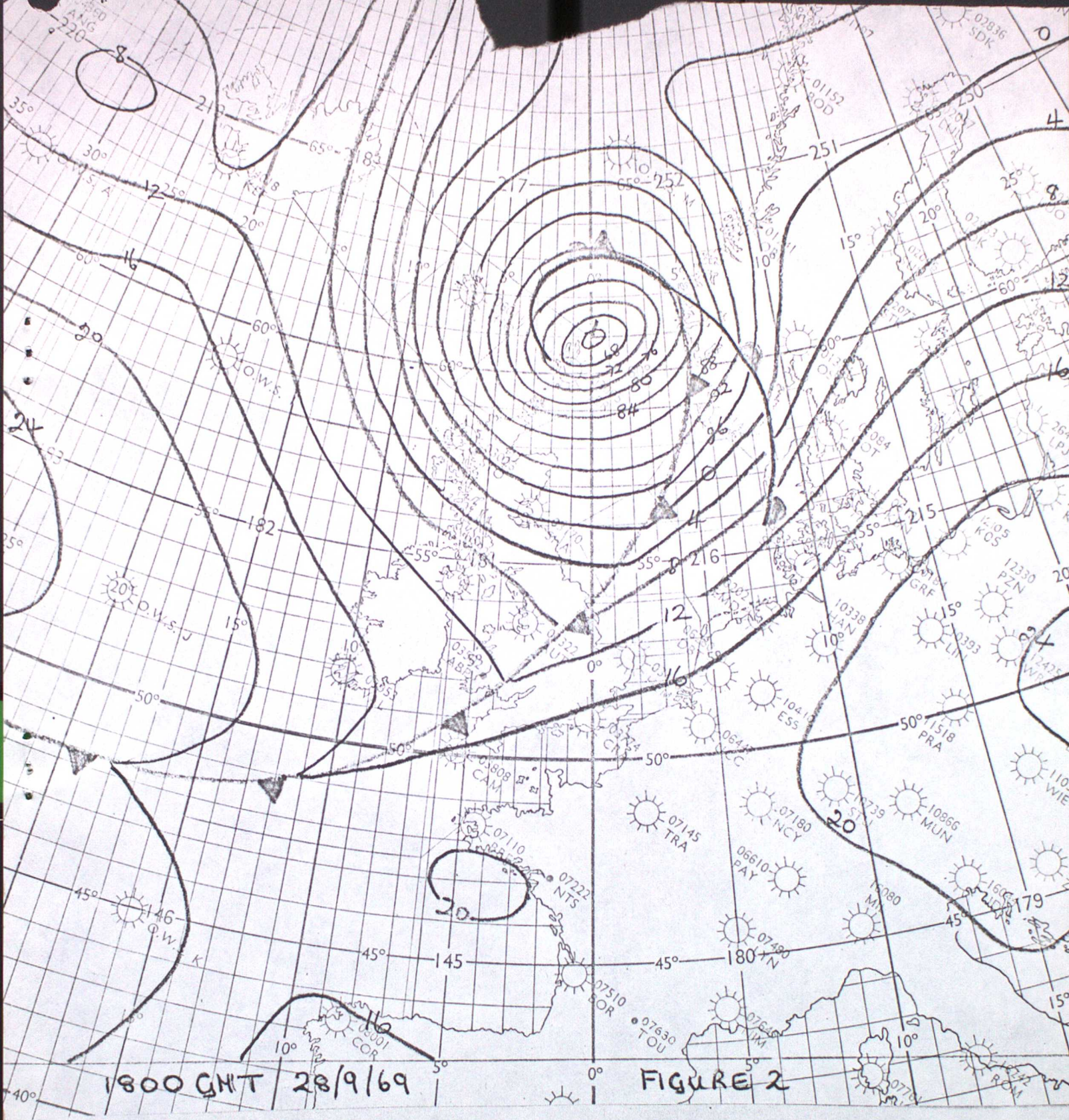

FIGURE 2

SURGE RESIDUAL DIAGRAM 2/69-70

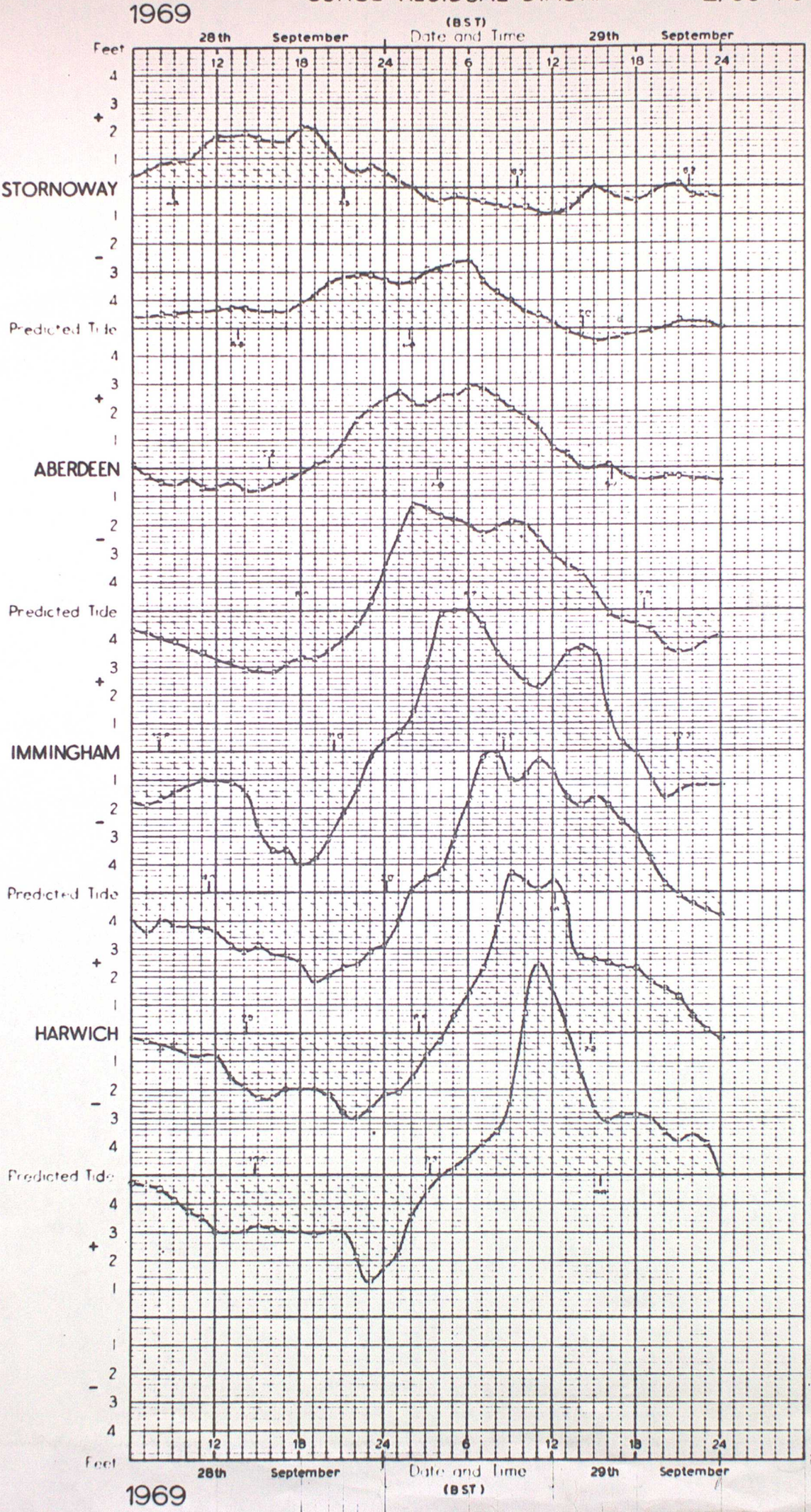

FIGURE 3

S.T.W.S. Met Office Bracknell

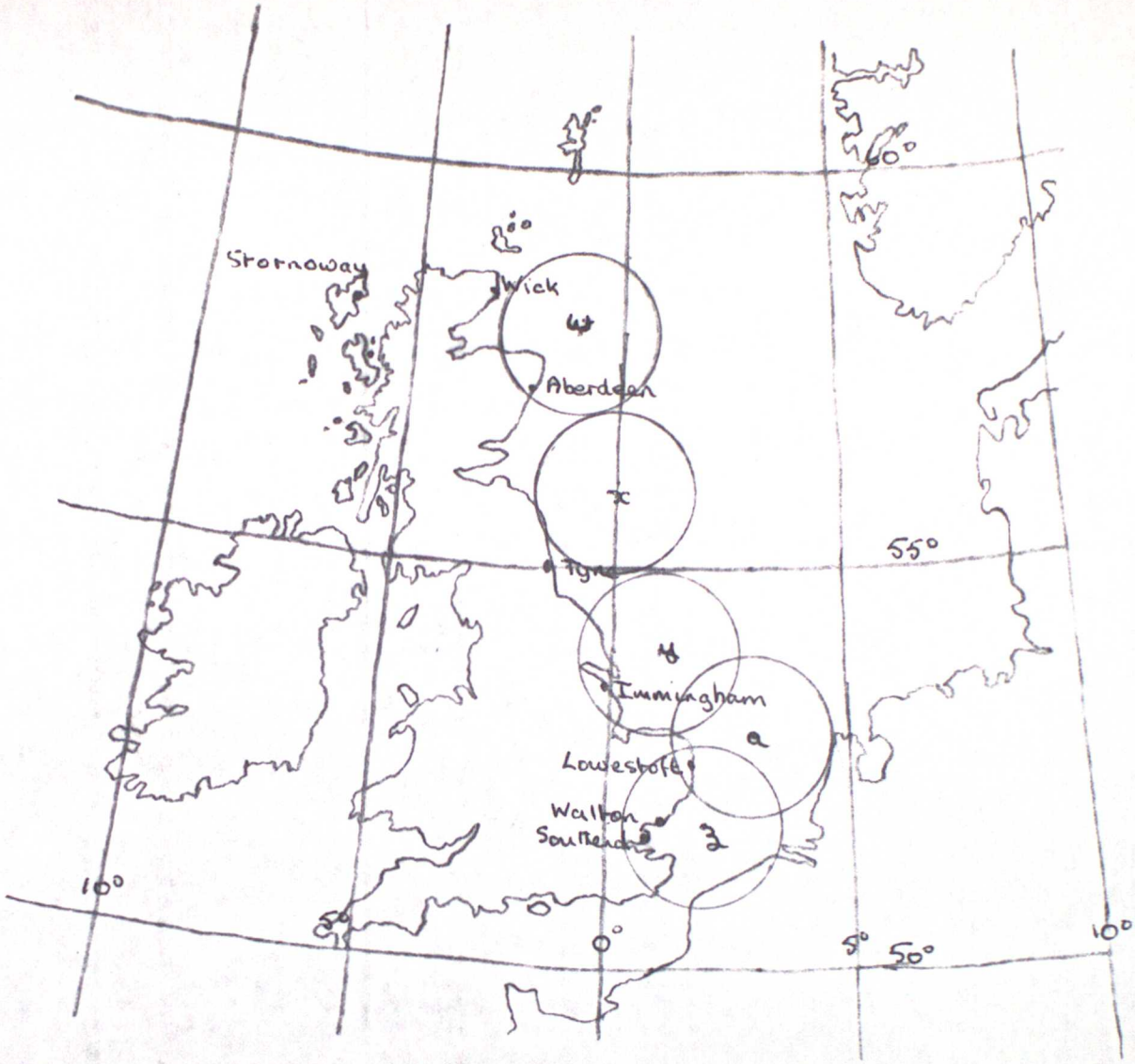

Fig 4. Reference Ports and Wind areas